

C. Tang Sah
University of Illinois
Urbana, Illinois 61801

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ABSTRACT

The dominant recombination phenomena which limit the highest efficiency attainable in silicon solar cells under terrestrial sunlight are reviewed. The ultimate achievable efficiency is limited by the two intrinsic recombination mechanisms, the interband Auger recombination and interband Radiative recombination, both of which occur in the entire cell body but principally in the base layer. It is estimated that an upper efficiency of 25.4% at AM1 or AM1.5 solar illumination can be attained if either Radiative or high-injection-level Auger recombination in the base is the only recombination loss mechanism in a cell with 50 micron thick base and at an absorbed photocurrent of 0.36 A/W. Thicker base will increase the efficiency slightly via higher absorbed photocurrent less higher Auger and Radiative recombinations in the larger volume. At 500 micron, the photocurrent is raised by 10.6% and the open-circuit voltage is reduced by about 60 mV due to larger recombination volume, giving a net efficiency gain of only about 0.6% to 26% at AM1. The low-level Auger recombination in the base gives a smaller efficiency of 24% in 50-micron base cell. This suggests that an optimum (26%) cell design is one with lowly doped 50-100 micron thick base, a perfect BSF, and zero extrinsic recombination such as the thermal mechanism at recombination centers (the Shockley-Read-Hall process) in the bulk, on the surface and at the interfaces. The importance of recombination at the interfaces of a high-efficiency cell is demonstrated by the ohmic contact on the back surface whose interface recombination velocity is infinite. To attain the Auger-recombination-limited efficiency in the base without a minority-carrier-blocking back-surface-field layer, the total majority carrier density in the base must exceed 10^{17} cm^{-2} , an impractically large value requiring a one-centimeter thick cell at a doping concentration of 10^{17} cm^{-3} which would increase Auger and Radiative recombination by 200 over a 50 micron cell and reduce the limiting efficiency by 5% to 20%. The importance of surface and interface recombination is further demonstrated by representing the Auger and Radiative recombination losses by effective recombination velocities which are about 0.33 and 3.1 cm/s respectively at 25.4%. Thus, to reach the ultimate efficiency limit of 25.4%, real interfaces must have recombination velocities less than about $10^{-17} N_s$ or 1 cm/s at a surface impurity concentration of $N_s = 10^{17} \text{ cm}^{-3}$. The paper is concluded by demonstrating that the three highest efficiency cells (17,18,19%) may all be limited by the SRH recombination losses at recombination centers in the base layer. To reach the Auger and Radiative recombination-limited efficiency of 25.4%, the SRH recombination loss in the base must be decreased to give a minority carrier lifetime greater than $2 \times 10^{14} / N_B$ or 2 ms at 10^{17} cm^{-3} base doping density. This corresponds to a dark current of 0.2 fA/cm² in the ideal diode law.

I. INTRODUCTION

Energy loss by photogenerated electrons and holes through scattering and recombination limits the ultimate performance of solar cells. Scattering reduces the mobilities of electrons and holes, increases the series resistance and decreases the fill factor (FF). Recombination increases the shunt conductance and the dark leakage current and decreases both the open-circuit voltage (V_{OC}) and the short-circuit current (J_{SC}). Energy loss during these two collision processes (scattering and recombination) will reduce the maximum efficiency (EFF) which is given by $EFF = FF * V_{OC} * J_{SC} / P_{IN}$ at an absorbed areal solar power density of P_{IN} .

The ultimate efficiency is limited by two intrinsic recombination mechanisms in an ideal cell structure in which the scattering or series resistance loss and the extrinsic recombination losses are reduced to negligible levels. These two intrinsic recombination mechanisms are the interband (conduction-band to valence-band) radiative process and the inter-band Auger process. The interband Radiative recombination mechanism poses the ultimate limit while the interband Auger recombination mechanism may be reduced by proper cell design via dopant impurity density and layer thickness control. In a silicon p+/n/n+ or n+/p/p+ back-surface-field (BSF) cell design with 50 micron base layer thickness, the ultimate AM1 (or AM1.5) efficiency is about 25% at room temperature and both the Radiative and Auger mechanisms contribute about equally to the recombination loss.

This paper presents an analysis of the effects of the intrinsic and extrinsic recombination mechanisms on the performance of silicon p/n junction solar cells. Section II provides a review of the recombination mechanisms and locations and their effects on the performance of solar cell devices. Section III provides an analysis of the ultimate performance of ideal cells with no scattering losses. Section IV illustrates the effect of surface recombination and its large degrading effect on performance. Section V gives an analysis of the three highest-efficiency single-crystalline silicon solar cells which have been reported. It delineates the material factors which may have reduced their measured performance below that predicted by ideal diode law. A short concluding summary is given in Section VI.

II. RECOMBINATION MECHANISMS AND SITES

The electron-hole recombination processes can be categorized according to their origin. They can be further divided by the energy exchange mechanisms which control the recombination rate. Recombination processes with the intrinsic origin are those which limit the ultimate performance of a solar cell. Recombination processes due to imperfections in the crystal lattice, grouped by their extrinsic origin, such as chemical impurities and physical defects, can be reduced so that their deleterious effects on cell performance can be nearly eliminated. A categorization of these recombination processes are given below [1].

INTRINSIC MECHANISMS (Interband Transitions)		ENERGY EXCHANGE PARTNER
I.1	Thermal Recombination	Phonons(Lattice Vibration)
I.2	Radiative Recombination	Photons
I.3	Auger Recombination	Third Electron or Hole
EXTRINSIC MECHANISMS (Band-Bound Transitions)		ENERGY EXCHANGE PARTNER
E.1	Thermal Recombination (SRH)	Phonons
E.2	Radiative Recombination	Photons
E.3	Auger Recombination	Third Electron or Hole

A main fundamental difference between the intrinsic and the extrinsic recombination mechanisms is that the initial and the final states of the electron are in different bands separated by a large energy gap for the intrinsic processes. The energy exchange during the transition is much larger than the largest phonon energy, about 60 meV in solids. While for the extrinsic processes, the initial or final states is a bound state localized at a lattice imperfection, either an impurity or defect site, while the other is an unlocalized band state. The energy exchange covers both the small energy range of the phonons as well as the large energies near the energy gap. Thus, the intrinsic processes cannot be eliminated completely, although the Auger process, I.3, can be reduced since it depends on the presence of a third electron or hole and hence will dominate only in regions of high electron or hole concentration. However, the extrinsic processes can be reduced to negligible level so that they no longer affect the solar cell performance. The reduction of the extrinsic recombination mechanisms requires crystal perfections and purities in starting silicon as well as stressless and clean solar cell fabrication processes which exceed the latest silicon very large scale integrated circuit (VLSI circuit) technology.

Among the recombination processes, the intrinsic Auger and Radiative mechanism pose the ultimate limit while the extrinsic thermal (SRH or Shockley-Read-Hall) mechanism is the current technology limit. The recombination rate of the SRH mechanism is proportional to the density of the impurities and defects. These imperfections can be unintentionally but readily introduced during the cell fabrication procedures and they may also be present in the starting crystal, having been incorporated during crystal growth. Thus, to reduce the SRH recombination rate will tax the latest silicon VLSI technology and beyond.

These recombination processes can occur preferentially at certain regions and locations of a solar cells which suggest device design and technology innovations to reduce and eliminate them. A schematic illustration is shown by a cross-sectional view of a p⁺/n/n⁺ cell in Fig.1. The recombination processes can occur in the quasi-neutral emitter p⁺, base /n/, and back-surface-field /n⁺ layers. They can also occur in the junction space charge layer of the p⁺/n junction, as well as at the oxide/Si and metal/Si or metal/oxide/silicon interfaces on the front and the back surfaces of the cell.

However, they are not all important in all of these regions. For example, in the highly-doped p⁺ emitter layer, only the interband Auger and the SRH recombination mechanisms may be important. The interband Auger recombination can be important if the majority carrier density in the quasi-neutral emitter exceeds about 1.0×10^{17} hole/cm² or a sheet resistance of about 0.6 ohm per square

since Auger recombination rate for the injected or photogenerated electrons in the p+ emitter layer is proportional to the square of the hole concentration, P^2 . For another example, the SRH recombination mechanism could also be important in the quasi-neutral p+ emitter if the density of the defect recombination centers is greatly increased due to the heavy doping of the p+ layer by incorporating a high concentration of boron impurity. Heavy doping introduces localized band-tail states and broadens the boron impurity level into an impurity band, both of which give a narrowing of the energy gap for the minority carriers or an increase of the intrinsic carrier density, n_i , or the minority carrier density. This would increase the minority carrier or electron recombination rate in the quasi-neutral emitter layer and reduce the solar cell performance. There has been no concrete evidence showing the importance of the localized or band-bound Auger recombination process (E.3) in the heavily doped emitter, although it is anticipated due to both the large majority carrier density and high density of defect and dopant impurities.

In the quasi-neutral base layer, the interband Radiative, interband Auger, and the SRH processes may all be important. The Radiative process in the base layer is the ultimate performance limiting loss mechanism. It is not as important in the emitter since the emitter layer is rather thin and hence has a rather small recombination volume compared with the thicker quasi-neutral base layer. The interband Auger process in the base layer can be reduced by not-so-heavily doping the base. Lightly doped base would enhance the influence of recombination in the back-surface-field layer so base doping must be optimized or not so low, resulting in significant loss from the interband Auger recombination process.

Similar to the emitter, the dominant recombination processes in the heavily-doped quasi-neutral back-surface-field layer are the interband Auger and the SRH recombination processes, but their influences are not as large as they are in the emitter since the emitter is close to the solar source and the minority carrier collecting p+/n junction than the BSF layer.

Surface recombination can also seriously limit the efficiency of very-high-efficiency solar cells. Recombination of electrons and holes at exposed surfaces and interfaces can occur via the various mechanisms just described. However, the interfaces, such as the oxide/silicon, metal/silicon and metal/thin-oxide/silicon interfaces which can be present in a cell, are layers of high density of defects and impurities. The defects, commonly known as dangling bonds, and the impurities can form electron and hole bound states and serve as sites for electron-hole recombination. Generally, the SRH mechanism at these interface bound states is thought to be the most dominant. However, for heavily doped emitter and BSF layers, the surface concentration of the majority carrier is so high that one could also expect the Auger mechanisms to be important, especially the interband type although the bound-band type has not been eliminated as a candidate. In silicon solar cells of greater than 20% efficiency, the recombination loss in the cell must be so low that even a minute amount of recombination at the interfaces can be very detrimental to achieving higher efficiency. At the ultimate efficiency of about 25%, an effective interface recombination velocity of 1 cm/s or less must be required to render interface recombination unimportant. This places a severe constraint on the high temperature processing steps used during cell fabrication to obtain low recombination velocity interfaces. Each increase of ten of the interface recombination velocity will reduce the open circuit voltage by

2.3kT/q or 59 mV at 24C and the efficiency by 10%. Fortunately, low interface-recombination-velocity processing techniques are well advanced in silicon VLSI technology. However, areal uniformity over the extremely large areas required of solar cells and stability are still two key unknown factors.

The requirement of low interface recombination velocity for reaching very high efficiency has motivated innovative cell designs. For example, the very high (nearly infinite) interface recombination velocity at the metal/Si contact of the front contacts of a cell has prompted one design to use all back surface contacts [2,3] and another design in which a thin oxide layer is introduced between the metal and the silicon surface to take advantage of the very low interface recombination velocity of the oxide/silicon interface [4,5]. Some of the latest high efficiency silicon solar cells, recently reported, seem to have the interface recombination loss reduced to a negligible level compared with the recombination loss in the quasi-neutral base layer [4,5,6]. Some quantitative analyses on these cells are given in section V.

Another important recombination loss originates from impurity-defect clusters in the bulk of the cell [7] and damaged and at the exposed perimeter surface of the p+/n and n/n+ high/low junctions of the cell [8]. In principle, these recombination sites can be eliminated by revising processing procedures and cell structure designs.

III. ULTIMATE PERFORMANCE OF IDEAL CELLS

The ideal cell is one that has only the lowest intrinsic recombination losses, the interband Radiative and interband Auger recombination losses. Operating in the low injection level is also desired to further minimize any SRH recombination losses and in particular, to take advantage of the more box-like current voltage characteristics given by the ideal diode law, $J=J_1[\exp(qV/kT)-1]$ compared with the high level law, $J=J_2[\exp(qV/2kT)-1]$ which has a more rounded or soft shoulder.

In the following subsections of this section, the ideal diode cell will be analyzed to illustrate the numerical range of the solar cell parameters, JSC, VOC, FF and a diode parameter, the dark current J1, in very high efficiency cells. This is followed by an analysis to give projected ultimate performance limit if the only losses left are the intrinsic Radiative and Auger processes. In the next section, section IV, the importance of surface recombination is illustrated by two design examples. In the last section, section V, analyses of the three highest efficiency cells recently reported are analyzed based on the ideal diode cell model given here.

3.1 IDEAL DIODE CELL

The d.c. current-voltage equation of a diode solar cell is given by

$$J = J_L - J_1[\exp(qV/kT) - 1] \\ - J_m[\exp(qV/mkT) - 1]$$

where J_L is the photocurrent density (areal), J₁ is the dark leakage current of the ideal Shockley p/n junction diode, m and J_m are the reciprocal slope

and dark current of the nonideal junction diode. $m=1$ to 2 for recombination in the space charger layer of the p/n junction [9]. $m=2$ for recombination in the quasi-neutral base layer at high injection level, i.e. when $N \gg P \gg \text{Dopant Density}$. $m=4$ if a surface channel exists across the p/n junction perimeter such as the inversion channel of a MOSFET [9]. If a shunt resistive path exists across the bulk or the surface of the junction, m can be greater than 4 [9]. For the interband Auger recombination mechanism, $m=1$ at low injection level but drops to $m=2/3$ at high injection level. This occurs because the interband Auger recombination rate is proportional to $N P + P N$ while quasi-neutrality at high injection levels requires that $N=P=n \cdot \exp(qV/2kT)$, resulting in a current law proportional to N^3 or P^3 or $[\exp(3qV/2kT)]$.

For high efficiency cells, all the nonideal recombination losses are eliminated except the interband Auger mechanism at high injection level. Thus, the J_m term can be dropped except for the interband Auger process. The ideal diode solar cell equation is then given by

$$J = J_L - J_1 [\exp(qV/kT) - 1].$$

The photocurrent, J_L , is a weak function of recombination loss for very-high-efficiency cells. It can be taken as a constant and set to the maximum available photocurrent for a given cell thickness. In the numerical analyses to be presented in this paper, $J_L = 36 \text{ mA/cm}^2$ will be assumed for a AM1.5 spectra at a photon power $P_{IN} = 100 \text{ mW/cm}^2$. This closely approximates the photocurrent of the measured AM spectra which gives 31.49 mA/cm^2 at 88.92 mW/cm^2 photon power in a cell of 50 micron thick under one pass with no front surface reflection, presented earlier [10] based on the spectra of Thekaekara. For other conditions and cell thicknesses, only the ratio, $J_L/P_{IN} = 36/100 = 0.36 \text{ A/W}$ needs to be modified. This photoresponse increases to 0.4594 A/W when the cell becomes infinitely thick or all the photons are absorbed, a 27.6% increase. To reach higher efficiency, the cell thickness may be increased to increase the short-circuit current, but this will increase the recombination volume so that a optimum thickness will be reached beyond which the efficiency will drop. Multiple passes using back-surface optical reflector in a thin cell can avoid the high recombination loss in the base of a thick cell.

The relationship between the short-circuit current, J_{SC} , and the open-circuit voltage, V_{OC} , is then given by

$$J_{SC} = J_L = J_1 [\exp(qV_{OC}/kT) - 1].$$

The maximum power point can be computed, without any approximation by setting $d(J \cdot V)/dV = 0$. The efficiency, EFF , at the maximum power point is then given by

$$EFF = P_{MAX}/P_{IN} = J_{MAX} \cdot V_{MAX}/P_{IN}$$

which is also used to define the fill factor, FF , given by

$$FF = J_{MAX} \cdot V_{MAX}/J_{SC} \cdot V_{OC}.$$

Thus, the maximum efficiency is given by

$$EFF = FF \cdot J_{SC} \cdot V_{OC}/P_{IN} = (J_{SC}/P_{IN}) \cdot FF \cdot V_{OC} = 0.36 \cdot FF \cdot V_{OC}.$$

This is a familiar result which has been used to analyze high efficiency cell designs. To illustrate the numerical range of the parameters in the very-high efficiency cells, a set of values are computed and tabulated in Table I. It shows that the dark current, J_1 , must be less than $2\text{E-}13 \text{ A/cm}^2$ or 0.2 pA/cm^2 for a 20% cell. It decreases one decade for each efficiency rise of 2%, reducing to 0.2 fA/cm^2 at 26%, which is about the ultimate limit for a 50 micron thick cell. The table also shows that for each 2% rise of efficiency, the open-circuit voltage is increased by 60 mV, consistent with the simple estimate we made earlier, 58.96 mV.

TABLE I
PERFORMANCE PARAMETERS OF VERY-HIGH-EFFICIENCY
IDEAL DIODE SILICON SOLAR CELLS
(AM1 or AM1.5, 24.0C)

SOURCE	J_1 (A)	J_{SC} (mA)	V_{OC} (mV)	FF	EFF (%)
Theory	2.0×10^{-16}	36.0	840	0.8664	26.0
Theory	2.0×10^{-15}	36.0	780	0.8588	24.0
Theory	2.0×10^{-14}	36.0	720	0.8501	22.0
Theory	2.0×10^{-13}	36.0	660	0.8402	20.0

3.2 ULTIMATE PERFORMANCE

The ultimate performance is limited by the interband Radiative and Auger recombination mechanisms. The ultimate efficiency is reached when all the extrinsic recombination losses are eliminated. The numerical results are obtained by assuming also that all the emitter recombination losses are negligible, especially the low-level interband Auger recombination loss in the highly doped quasi-neutral emitter layer. This is achievable by proper design of the emitter concentration profile so that the total majority carrier density in the emitter is not much higher than about $1\text{E}14$ and there is a good p^{++}/p^+ front surface field layer to maintain the high sheet conductance and low series resistance. Thus, in this limit where only base recombination dominates, the dark current, J_1 can be readily obtained by multiplying the position independent base recombination rate to the base thickness. The results for both the two intrinsic loss mechanisms and the SRH extrinsic mechanisms are listed next.

Radiative Recombination (Interband)

$$J_1 = qC^0 * XB * n_i^2$$

Auger Recombination (Interband)

$$J_{0.6} = qC^a * XB * n_i^3 \quad (\text{High Level})$$

$$J_1 = qC^a * XB * n_i^2 * NB \quad (\text{Low Level})$$

Thermal Recombination (Bound-Band) SRH

$$J_1 = q\tau_B^{-1} * XB * n_i^2 / NB \quad (\text{Low Level})$$

$$J_2 = q\tau_B^{-1} * XB * n_i \quad (\text{High Level})$$

Numerical calculations are performed for silicon cells with base layer thickness of $XB=50$ microns at 24.0°C where $n_i=1.0\text{E}10 \text{ cm}^{-3}$. The Radiative recombination rate of $C^0 n_i^2=0.62\text{E}6$ is employed while the interband Auger rates are: $C^0=2.8\text{E}-31$ and $C_p=0.99\text{E}31 \text{ cm}^6/\text{s}$. To illustrate the condition at which the SRH recombination loss will reduce the ultimate efficiency, a base lifetime of 100 us and diffusivity of $20 \text{ cm}^2/\text{s}$ are assumed.

The results are tabulated in Table II. This table also shows the results of two ohmic-contact cells to illustrate the effect of surface and interface recombination. They are discussed in the next section.

Table II shows that the ultimate efficiency limited by Radiative recombination alone is about 25%. The Auger limits are computed for the extremes of the injection levels and both are close to the 25% Radiative limit. The high injection limit of the Auger case is reached if the majority carrier or doping impurity concentration in the base layer is less than about $5\text{E}16 \text{ cm}^{-3}$ for the 50 um base thickness which gives a total carrier density in the base of $2.5\text{E}14 \text{ cm}^{-3}$. Designing and operating the cell in the high level Auger range by reducing the base doping may help in maintaining the high SRH recombination lifetime which is necessary to achieve the high efficiency, but the sensitivity to surface recombination becomes more severe at this high level as indicated in the table and discussed in the next section.

Table II also gives the results of SRH recombination loss at both low and high injection levels. Two design ideas may be drawn. (i) High level injection should be avoided. This was arrived at previously by a simple observation that the high level recombination current law, $\exp(qV/2kT)$, gives a softer illuminated I-V curve and hence lower fill factor and efficiency. (ii) Table II also shows the condition at which SRH recombination loss will become important to lower the ultimate efficiency. The example assumes a SRH recombination lifetime of 100 us to give a 23% efficiency. To reach 25%, the SRH base lifetime must be greater than about 1000 us or 1 ms which is at the limit of the state-of-the-art for VLSI grade silicon crystals.

TABLE II

ULTIMATE PERFORMANCE OF SILICON SOLAR CELLS
(Including the Effect of Surface Recombination)

SOURCE	J_1 (A)	J_{SC} (mA)	V_{OC} (mV)	FF	EFF (%)	m	J_1/q	S_{EFF} (cm/s)
Radiat. Recomb.	5.0×10^{-16}	36.0	817	0.8637	25.4	1	$C^u x_B n_i^2$	3.1
Auger H	3.0×10^{-22}	36.0	786	0.8968	25.4	2/3	$C^a x_B n_i^3$	0.33
Auger L	2.3×10^{-15}	36.0	776	0.8582	24.0	1	$C^a x_B n_i^2 N_B$	14
SRH L	8.0×10^{-15}	36.0	746	0.8540	23.0	1	$\tau_B^{-1} x_B n_i^2 N_B^{-1}$	50
Ohmic L	6.4×10^{-13}	36.0	634	0.8354	19.1	1	$D x_B^{-1} n_i^2 N_B^{-1}$	4000
SRH H	8.0×10^{-8}	36.0	666	0.7415	17.8	2	$\tau_B^{-1} x_B n_i$	50
Ohmic H	6.4×10^{-6}	36.0	442	0.6645	10.6	2	$D x_B^{-1} n_i$	4000

$T=24^\circ\text{C}$; $n_i=10^{10} \text{ cm}^{-3}$; $\text{Area}=1 \text{ cm}^2$; $x_B=50 \text{ } \mu\text{m}$; $N_B=10^{17} \text{ cm}^{-3}$; $D=20 \text{ cm}^2/\text{s}$;

$\tau_B=100 \text{ } \mu\text{s}$; $P_{IN}=100 \text{ mW (AM1.5)}$; L=Low Level; H=High Level;

$C_{n_i}^0=0.62 \times 10^6$; $C_L^a=C^n=2.8 \times 10^{-31} \text{ cm}^6/\text{s}$; $C_H^a=C^n+C^p=3.8 \times 10^{-31} \text{ cm}^6/\text{s}$.

IV. EFFECTS OF SURFACE AND INTERFACE RECOMBINATION

The influence of surface and interface recombination on the efficiency of high efficiency cells is quite large, which has been both demonstrated in the laboratory [4,5,6] and recognized from simple device modeling. The latter will be presented in this section.

To provide a quantitative idea of the importance of recombination at the surfaces and interfaces of a solar cell, the bulk recombination losses may be written in terms of an effective recombination velocity so that its magnitude can be compared with the surface and interface recombination velocity at the real surfaces and interfaces of a solar cell. This effective recombination velocity can be defined both at the low and high injection levels. In the following two subsections, 4.1 and 4.2, the effect of surface recombination will be considered for two cases.

4.1 THE EQUIVALENT RECOMBINATION VELOCITY OF A BULK RECOMBINATION PROCESS

The equivalent recombination velocity of a bulk recombination process which occurs in a volume element, such as the base region, can be defined as that velocity at the minority carrier entrance surface which would produce the same recombination current. These are illustrated in Fig.2 for several recombination locations, some of which are the true interface recombination velocities and others are the equivalent recombination velocities. For example, SE and SB are the equivalent recombination velocities of the quasi-neutral emitter and base layers at the minority carrier entrance or injection interfaces. The true interface recombination velocity illustrated in Fig.2 is SFI, the recombination velocity at the front oxide/silicon interface. Another equivalent recombination velocity in Fig.2 is SBI which is the effective recombination velocity of minority carriers flowing into the n+ BSF layer at the n/n+ entrance surface.

These equivalent recombination velocities may be explicitly defined to give accurate numerical estimates on the importance of true interface recombination loss. They are defined through the dark current density,

$$J_1 = q \cdot P_B \cdot S_B + q \cdot N_E \cdot S_E$$

which, when combined with the dark current expression listed in Table II and section 3.2, gives

$$S_B = (X_B / \tau_B) + S_{BI} + S_{BA} + S_{BO}$$

and

$$S_E = (X_E / \tau_B) + S_{FI} + S_{EA} + S_{EO}$$

Here, X_B and X_E are the base and emitter layer thickness; S_{BI} and S_{FI} are the effective and real recombination velocity at the back and front interfaces; S_{BA} and S_{EA} are the effective recombination velocities from volume interband Auger recombination in the quasi-neutral base and emitter layers; and S_{BO} and S_{EO} are those from volume interband Radiative recombinations. These especially simple expressions are applicable for base and emitter layers which are thin compared with the minority carrier diffusion length, a condition that holds well in a high efficiency cell. They are given by

$S_{BT} = X_B / \tau_B$	(All Level SRH)
$S_{BA} = C^a \cdot X_B \cdot N_B^2$	(Low Level Auger)
$S_{BA} = C^a \cdot X_B \cdot n_i^2 \exp(qV/kT)$	(High Level Auger)
$S_{BO} = C^0 \cdot X_B \cdot N_B$	(All Level Radiative)

for the base layer, and a similar set for the emitter layer.

The numerical values are computed and listed in Table II. It is evident that the effective recombination velocities of the limiting loss mechanisms are extremely low at the ultimate 25% efficiency. The value of 3.1 cm/s for the Radiative recombination loss to give the 25.4% efficiency illustrates the importance to have low surface recombination interfaces. Unless the interface recombination velocity is reduced substantially below 3.1 cm/s, recombination losses at the interfaces will seriously reduce the efficiency.

The rather small value of 0.33 cm/s for the high-level Auger limit shown in Table 2 illustrates the large carrier density and the very high Auger recombination rate in the base. This makes the dependence on the surface recombination even more sensitive.

4.2 EFFECT OF OHMIC CONTACT AND THE BACK-SURFACE-FIELD

Table II gives another example which illustrates the importance of having a back surface field layer to reduce the effect of back surface recombination loss. This example arises from the question: Can the back surface field layer be replaced by a thick base and still have a very high efficiency? This is a practical question since the BSF layer requires extra cell fabrication processing at high temperatures which usually reduces the bulk lifetime in the quasi-neutral base.

Since a thick base means more Auger and Radiative recombination loss, an ideal device model can be set up to answer the above question. In this mode, the only recombination in the base is the minute Auger and Radiative recombination and there is no BSF so that the injected minority carriers face the full recombination at the Si/metal contact on the back surface. The interface recombination velocity at the back Si/Metal interface is assumed to be infinite or a perfect ohmic. Then, the dark current due to this component is given by

$$J_1 = q \cdot DB \cdot X_B^{-1} \cdot (n_1^2 / n_B); \quad SB = DB / X_B \text{ (Low Level)}$$

and

$$J_1 = q \cdot DB \cdot X_B^{-1} \cdot (n_1); \quad SB = DB / X_B \text{ (High Level)}$$

To determine the thickness required to reduce the effect of interface recombination at the back surface below that of Auger recombination in the [uasi-neutral emitter, we set the two recombination velocities or J_1 equal. Consider the low level case, we have

$$X_B \cdot C^a \cdot n_B \cdot n_1^2 = DB \cdot n_1^2 / (n_B \cdot X_B)$$

or

$$n_B \cdot X_B = \text{SQRT}(DB / C^a) = \text{SQRT}(20 / 2.8E-31) = 1.0E16 \text{ cm}^{-2}$$

Thus, for a base doping of $n_B = 1.0E17$, we need to have a base thickness of $X_B = 1000 \mu\text{m} = 1 \text{ mm}$, an impractical result. This shows the importance of having a good high-low potential barrier on the back surface to reduce the back surface recombination loss.

IV. EVALUATION OF THREE RECENT HIGH-EFFICIENCY CELLS

Silicon solar cells with efficiency approaching 20% (AM1) have been fabricated in the laboratory. Innovative cell designs have been developed to reduce interface and emitter recombination losses. In this section, the experimental data of the best cells of three industrial laboratories are compared with that predicted by the ideal diode cell theory which was used to produce Table I. From a comparison of the theory and experiments, it appears that bulk recombination in the quasi-neutral base via the SRH mechanism is the limiting loss on all three cells.

The experimental and computed cell performance parameters are tabulated in Table III. The first three rows are for the highest performance cell from Green [4] and listed in the first row. The computed results are all higher than the measured values, suggesting effects from several sources.

TABLE III
PERFORMANCE OF THREE HIGHEST EFFICIENCY SILICON SOLAR CELLS AND
COMPARISON WITH IDEAL DIODE CELL THEORY

SOURCE	J_1 (A)	J_{SC} (mA)	V_{OC} (mV)	FF	EFF (%)
Theory	3.2×10^{-13}	35.6	660	0.8402	19.7
Theory	6.6×10^{-13}	35.6	641	0.8350	19.0
GREEN	3.2×10^{-13}	35.6	641	0.822	18.7
Theory	1.2×10^{-12}	35.9	627	0.8340	18.8
SPITZER	---	35.9	627	0.800	18.0
Theory	2.0×10^{-12}	36.2	605	0.8296	18.2
Theory	2.4×10^{-12}	36.2	600	0.8286	18.0
ROHATGI	2.0×10^{-12}	36.2	600	0.793	17.2

The second two rows are for the best cell from Spitzer [5]. The theory is computed using the measured $J_{SC}=35.9$ and $V_{OC}=627\text{mV}$. The larger computed fill factor, 0.8340 compared with measured 0.800 suggests possible series resistance loss in the actual cell which is not accounted for in the ideal diode cell model.

The third three rows are for the best cell from Rohatgi [6] which is a higher resistivity cell (4 ohm-cm versus the 0.1 to 0.3 ohm-cm of Green and Spitzer). The first theory row is based on the measured $J_1=2\text{E-}12$ and $J_{SC}=36.2$ which gives $V_{OC}=605\text{mV}$, $FF=0.8296$ and $EFF=18.2\%$. The measured V_{OC} and the theory are quite close, only 5 mV different, and the lower observed efficiency is mainly due to the lower experimental fill factor which again suggests possible series resistance losses in the real cell.

In all three cases, the computed and the measured cell performance data are quite close, indicating that low level recombination in the quasi-neutral base layer via the thermal or Shockley-Read-Hall mechanism at defect and impurity recombination sites is the dominant loss mechanism. Further

improvement to achieve efficiency greater than 20% must depend first on identifying the base recombination center species and then reducing their density further. Although emitter bulk and surface recombination are substantially reduced in these three cells so that they are not important at less than 20%, these losses may be important again and must be further reduced at higher efficiencies.

VI. CONCLUSION

Interband Auger and Radiative recombination losses in the base layer limit the AM1 efficiency to about 25% in silicon solar cells with a base thickness of about 50 microns. Increasing the thickness will increase the efficiency only slightly, via higher short-circuit current. In order to eliminate the influence of recombination losses in the base due to the SRH thermal recombination mechanism at impurity and defect centers, the base lifetime must be greater than about 1 ms or an equivalent recombination trap density of less than $1 \times 10^{11} \text{ cm}^{-2}$. In addition, all interface and surface recombination losses must also be reduced to give a effective recombination velocity of less than about 1 cm/s. These very stringent requirements indicate that the latest state-of-the-art silicon VLSI technology is needed to provide the nearly perfect silicon crystal and the very clean and low-stress fabrication techniques which are necessary to produce very-high-efficiency solar cells that will approach the ultimate theoretical limiting efficiency.

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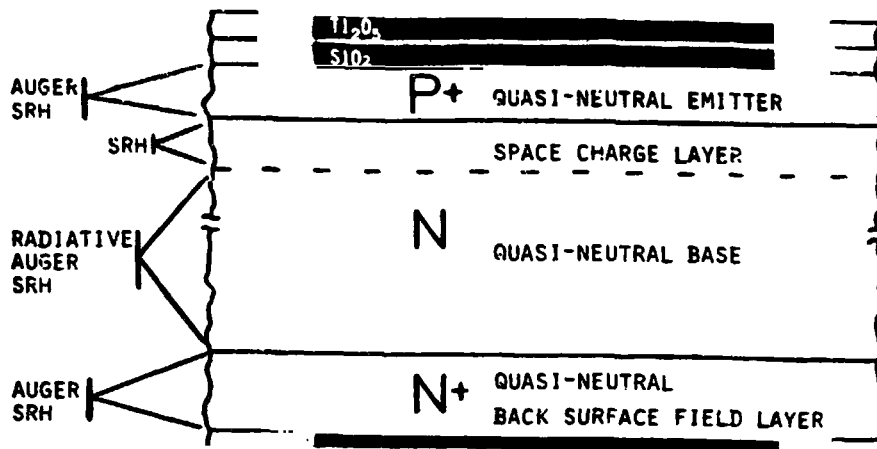


Figure 1 A cross-section view of solar cell showing the dominant recombination processes and locations. RADIATIVE and AUGER are the interband radiative and Auger recombination mechanisms. SRH is the Shockley-Read-Hall thermal recombination at defect and impurity recombination centers. Recombination occurs both in the bulk layers and at the interfaces between oxide, silicon and metal(dark).

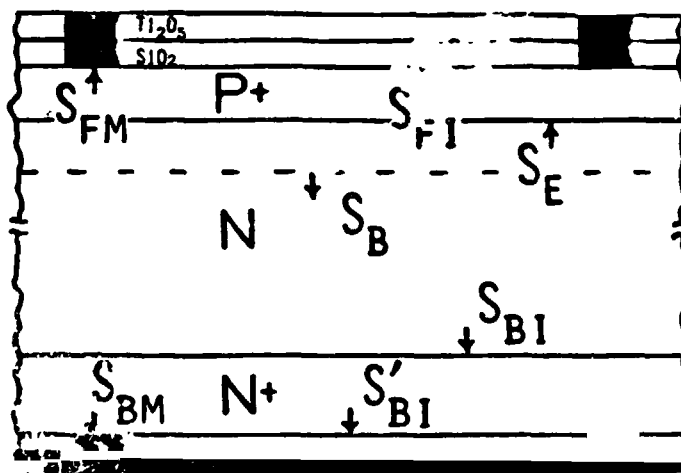


Figure 2 A cross-section view of solar cell showing the recombination velocity representation of the recombination rates. S_E , S_B and S_{BI} are the effective recombination velocities of volume recombination processes. S_{FI} , S_{FM} , S'_BI and S_{BM} are the real interface recombination velocities at the front oxide/silicon, front metal/silicon, back oxide/silicon and back metal/silicon interfaces.

DISCUSSION

PRINCE: While we have this slide on here, if you remove the very heavy doping on the surface, how would that affect the efficiency?

SAH: We can do a quick calculation. Let me just illustrate this with a view-graph so you can see how to go about doing that.

TAN: Can I make a comment? I have done a similar calculation by taking the tail off and I see a V_{oc} goes up by about 20 millivolts. If you start with 10^{19} and come all the way down, your V_{oc} goes up by 20 millivolts.

SAH: My model here is based on all of these being from the emitter; then I can get a good agreement. If the base is not a limiting factor -- suppose it is not at all, it is just an emitter -- then it is going to make quite a substantial difference.

QUESTION: Where did the profile come from? Is that an experimental profile? Did that come from spreading resistance?

SAH: No. That is from SIMS.

LANDSBERG: I have a quick question about the possibility of radiative-limited lifetime. If that was ever achieved, or if that ever occurred, one would obviously have practically 100% radiative converter and although, in one way of looking at it, it is bad to have some limit on the efficiency by this recombination mechanism; I could perhaps take advantage of it. Do you think there is any example where the efficiency is really radiative-limited? It would be quite interesting, it is just a hypothesis.

SAH: I don't know of any example. The highest one that is recorded so far is still only 19%.

SCHRODER: If you drop the surface concentration more and more, what do you think happens to the contact resistance? Have you looked at that?

SAH: No. I have not taken any contact resistance.

LOFERSKI: Just what is the difference between the high and the low level Auger recombination?

SAH: The low-level Auger follows the ideal Shockley diode because the minority carrier density increases very little compared with base doping.